Investigation of the N-shaped environmental Kuznets curve for COVID-19 mitigation in the KSA

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Abstract

Climate change mitigation has led to a recent question regarding many policymakers and sustainable development goals (SDGs) of the Kingdom of Saudi Arabia (KSA) for Vision 2030. In 2019 and 2020, COVID-19 mitigation was the only issue the world raised questions about; for example, the KSA and the rest of the world are working diligently to meet COVID-19 mitigation targets. To assess policy supervision in terms of the ability to achieve COVID-19 targets, this survey examines the operators necessary to achieve the SDGs in regard to improving COVID-19 mitigation and increasing economic growth. In particular, we examine COVID-19 mitigation under the setting of an N-shaped environmental Kuznets curve (N-shaped EKC) in the KSA. To identify the COVID-19 shock in the KSA, the effects of oil price and oil rent on CO₂ emissions are examined. The results of the autoregressive distributed lag (ARDL) and non-autoregressive distributed lag (NARDL) bound testing approach indicate that due to the COVID-19 pandemic, the inverted N-shaped EKC hypothesis is validated in the long term. Empirically, we find that oil price strengthens the relationship of level, quadratic and cubic of economic growth and environmental quality while oil rent weakens this relationship. Additionally, the long-term incidences of positive shocks on oil price in the presence of COVID-19 outbreak are not similar to the negative shock to CO₂ emissions, implying the existence of asymmetric impacts on carbon dioxide emissions in long-term forms. Our research implies that an oil price shock could be judicious for macro guidance of the economy in the KSA. Our findings are helpful for policymakers and investors in terms of their settlement planning because they can be used to evaluate prospective courses of economic profitability under the COVID-19 shock.

Keywords COVID-19 · Shock analyses · Oil prices

JEL codes C23 · G15 · I12 · Q41

Introduction

The dialogue of facilitation stemming from the climate change summit (COP 24) in Pologne has examined several goals; that

is, global warnings issued by countries have become the most highlighted problem in the world (Duan et al. 2016). Furthermore, the principal goal is to achieve neutrality between greenhouse gas emissions and economic growth in

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the world, indicating a long-run equilibrium between environmental improvement and economic development, but the world is focused on COVID-19 mitigation on the one hand and economic growth on the other.

The recent global pandemic and actual reduction in oil prices have had a significant effect on economic growth and human well-being, especially in the health sector. On the other hand, COVID-19 mitigation can affect several sectors of the economy in direct and/or indirect ways. As a result, several studies have adopted general equilibrium modelling to estimate the mitigating effects of COVID-19 on economies by incorporating interactions between different sectors. In addition, sustainable development should point the economy towards the adoption of cleaner production, which has been generally proven by the validation of the EKC hypothesis. In this respect, although most of the work has focused on the validation of this null hypothesis, it cannot indicate and guarantee the maintenance of development and growth likely to guarantee the protection of the environment and ecosystems. Hence, the use of the N-shaped Kuznets curve allows us to either invalidate or confirm the durability of the relation between the environment quality and the GDP. Our study addresses this conundrum and explores the validity of the N-shaped environmental Kuznets curve.

In terms of preferences, a restrictive model should be used, but this type of model ignores highly exogenous variables such that the oil price, oil rent, and COVID-19 variables can overestimate the effect of the GDP on carbon dioxide emissions. Hence, there is a need to establish a variable in our model. Second, we avoid incorporating variables, as is the case in many studies, such as those on energy consumption and trade, which only amplifies the problems of endogeneity and redundancy in the GDP variable.

By December 2019, a new severe acute respiratory syndrome emerged in China, which surprised and even stunned the world owing to its ferocity and velocity of the related outbreaks. The so-called COVID-19 was soon considered by the World Health Organization (WHO) to be global pandemic with fatal consequences that has thoroughly upset the global equilibrium and consequently, each government strategy or plan at random, thus introducing uncertainty. The world has been faced with global lockdowns, a worldwide public health emergency, supply shortages, long-lasting time curfews, social distancing, employees working from home, and a lack of transportation; human beings should be committed to the famous slogan: Stay home, stay safe. During this time, governments' urgent objective became learning how to preserve their citizens from the lethal pandemic.

Fornaro and Wolf (2020) postulate that the new pandemic could generate a negative supply disruption in the global economy due to the limitation of all activities and a reduction in supply chains. The new COVID-19 has harshly affected both health and economic sectors. In addition to high rates of

mortality globally, the world has witnessed strong economic fluctuations. Accordingly, governments should develop short-run plans focused on increasing their various spending for the sake of containing the negative effects of the infectious pandemic.

Coronavirus has caused significant disruptions globally because of the state of uncertainty, confusion, and fluctuation that has trapped almost all economic veins of each country. Hence, many studies stress the fact that the COVID-19 pandemic has suddenly badly affected several macroeconomic variables, such as distribution, labor, transportation, aircraft traffic, education, inflation, crude oil prices, and economic growth.

Owing to this terrifying situation, governments have felt compelled to engage in such measures that could alleviate the heavy burden of COVID-19 by easing lockdown measures already imposed, limiting the curfew period, permitting various activities, even in the production, industrial, and transportation sectors. In addition to the severe effect of shutdowns and disruption in economic activities throughout the world, the global situation worsened due to the unexpected behavior of crude oil prices. It is very interesting to highlight that fluctuations in the crude oil market could have a large impact on macroeconomic determinants.

On March 10, 2020, the World Health Organization (WHO) announced that the new coronavirus had become a global pandemic, and later, the total number of confirmed cases of COVID-19 reached a world record. In the USA, the number of applications for unemployment benefits has significantly increased because of the limited labor supply. The situation in the USA became grave due to shrinking crude oil prices. Moreover, the USA was hit by a drop in the value of the US dollar due to changing exchange rates and the George Floyd case, which occurred simultaneously.

Recent studies considered that global quarantine generated an excess of supply rather than demand, consequently generating such a severe oil price drop. In reaction to a possible global economic turndown, OPEC attempted to diminish oil production to maintain prices. Nevertheless, Russia does refuse to slash production quotas. As a result, there was such an imbalance between supply and demand in the crude oil market, the global economic variables, and the exchange rate of US\$. At that moment, there was a relative accord between Russia and Saudi Arabia aiming to preserve the actual oil production level causing a wave of anxiety throughout the world, specifically in the USA.

Stock market crashes occurred on March 12, 2020. In fact, commodity (energy) markets seem tightly linked to recent economic problems. Consequently, energy markets appear to be promising for investors, hedgers, and speculators as an alternative instrument for hedging against high risk when conducting financial transactions on the equity market.

The global economic situation has worsened since the new pandemic has generated significant panic purchases, aircraft

traffic cuts, and supply shortages. The world trade cut down or even gets frozen. Furthermore, governments felt afraid about the higher rates of their public debt and fiscal deficit. Accordingly, global growth could drop at 2.4% rather than 2.9% expected.

Several studies have highlighted the correlation between crude oil prices and the economic activities of each country. Oil-exporting countries regard that a decline in crude oil prices may have a negative correlation with their economic growth. Yilmazkuday (2020) explained that the oil price reduction was in fact a consequence of the global disruption of industrial production, which severely depressed world demand. In response, the International Energy Agency declared in February 2020 that there was a total demand disruption of approximately 425,000 barrels per day, which compelled OPEC (2020) to adjust the oil supply to preserve crude oil prices, but this was done in vain since Russia was not cooperative and refused to be a part of any endeavor to control the oil supply. Later, fortunately, an agreement was formed between globally exporting powers (the USA, the Kingdom of Saudi Arabia (KSA), and Russia) and OPEC with the goal of putting an end to oil price drops.

Jorda et al. (2020) attested that this global pandemic has macroeconomic consequences such as returns to assets and cut investment opportunities. For instance, COVID-19 consequences on Saudi Arabia where the economic costs of the pandemic were hard to undergo. In this sense, the Saudi government has taken it in serious since the beginning of the SARS outbreak. It hurried up in order to contain the pandemic to open isolation and disease centers, support health facilities, and increase its expenditure and spending besides the periodic fuel prices regulation.

In fact, the KSA, an exporting oil country whose economy is excessively dependent on the revenues of its crude oil exportation, has been seriously harmed by the reduction in world prices. Furthermore, the Saudi incomes generated from crude oil exportation were reduced, largely proving the significant correlation between global oil prices and national economic growth. Furthermore, the Saudi Gross Domestic Product was significantly lowered since it mainly relies on crude oil revenues. In addition, there was a drop in manufacturing production activities and a serious reduction in labor demand.

Accordingly, Saudi authorities have acted promptly and firmly to ease the negative effect of COVID-19 throughout the kingdom by focusing rather on conducting macroeconomic measures such as the relaxation of lockdown measures, the reopening of various activity veins, and specifically the maintenance of tremendous spending to combat the fatal pandemic despite the total number of confirmed cases of COVID-19 of approximately 250,000 in July 2020.

Saudi Arabia has largely contributed to solving the problem of oil production quotas, mainly those of OPEC and Russia, reducing the tension among oil-exporting powers and eventually reaching an agreement insuring the recovery of crude oil prices.

During the COVID-19 outbreak, the KSA did its best not only to enhance its national payment balance but also to catch urgent local or foreign investments. Although this global new pandemic has seriously touched Saudi macroeconomic determinants, the policymakers in KSA seem to succeed in overcoming such a stubborn enemy by engaging in sustainable reforms and measures aiming at betterment of their national GDP.

As previously noted, the objectives of this study are to examine the relationships among CO₂ emissions, economic growth, oil price, oil rent, and COVID-19 by testing the validity of the N-shaped EKC hypothesis in the KSA and explore the possible asymmetric response of CO₂ emissions primarily to changes in the oil price level and the asymmetric response of carbon dioxide emissions to COVID-19 mitigation.

Literature review

According to proponents of the environmental Kuznets curve (EKC), first proposed by Grossman and Krueger (1991), the direct relationship between economic growth and environmental warming has an inverted U shape. De Bruyn et al. (1998) examined the environmental Kuznets curve in four developed economies (the Netherlands, the UK, the USA, and Western Germany), and the results showed that indicators show a positive relationship between economic growth and global warming. Kaufmann et al. (1998) explored the relationship between real income and the atmospheric levels of sulfur dioxide (SO₂). The results showed an inverted U-shaped relationship between economic activity and SO₂ concentrations. Cole (2004) suggested that the N-shaped relationship can be clarified by focusing on the trade and movement of the industrial sector between areas in the north and south. Lantz and Feng (2006) tested the environmental Kuznets curve in Canada over the 1970–2000 period. The empirical results of the macroeconomic variables and environmental warming showed an inverted U-shaped relationship between GDP per capita and carbon dioxide emissions. Torras and Boyce (1998) indicated that the relationship becomes N-shaped when technological change arises. The strength of the relationship is based on a reduced scale and scope to better classify industrial sectors.

First, there are various literature reviews that explain the EKC hypothesis with renewable energy (Apergis and Ozturk 2015; Al-Mulali et al. 2016; Sugiawan and Managi 2016). The inverted U-shaped linkage between environmental degradation and renewable energy in EU-27 countries during the period between 1996 and 2010 is confirmed by López-Menéndez et al. (2014). Bölük and Mert (2015) tested the EKC in Turkey over the period 1961–2010. The empirical estimation by an autoregressive distributed lag (ARDL)

approach shows a U-shaped environmental Kuznets curve between per capita economic growth and income. Allard et al. (2018) included renewable energy consumption in the examination of the N-shaped environmental Kuznets curve in 74 countries consisting of the period 1994 to 2012. A quantile regression estimation in the N-shaped EKC is validated in different developing countries. Furthermore, Yao et al. (2019) tested the relationship between carbon dioxide emissions, economic growth, and renewable energy. This research examines the nexus between these selected variables in six geo-economics between 1990 and 2014. Panel cointegration estimation makes up a U-shaped renewable Kuznets curve (RKC). Balsalobre-Lorente et al. (2018) showed that renewable electricity consumption had a positive impact on carbon dioxide emissions in Germany, France, Italy, Spain, and the UK from 1985 to 2016. The empirical findings denote the existence of an N-shaped environmental Kuznets curve between real GDP and carbon dioxide emissions. Bekhet and Othman (2018) found that an inverted N-shaped EKC hypothesis is confirmed for the Malaysian case over the period 1971–2015 using bounds cointegration tests between renewable energy consumption, carbon dioxide emissions, and economic growth. Yilanci and Ozgur (2019), testing G7 countries, found that a U-shaped template was validated in Japan and the USA and an inverted U-shaped template was validated in Canada, France, Germany, Italy, and the UK by bootstrap rolling window causality.

Second, in recent years, various studies on the impact of climate change on environmental warming have indicated that climate change can negatively affect economic growth. Khan et al. (2016) tested the relationship between climate change and the environmental Kuznets curve (EKC) in developing countries over the period 2000–2013. The empirical estimation by the generalized method of moments (GMM) showed a U-shaped EKC in the relationship between climate change and per capita GDP. Özokcu and Özdemir (2017) found an N-shaped EKC in the relationship between environmental degradation and economic growth during the period 1980–2010 in 26 OECD countries for the first model and an inverted N-shaped EKC for 52 emerging countries for the second model. Jiang et al. (2019) investigated the environmental Kuznets curve threshold in 39 countries by using an input-output approach. The relationship between the mitigation of carbon dioxide emissions and trade had an inverted U-shape and then an N-shape. Wang (2019) showed that biomass energy consumption is crucially linked to environmental degradation by studying a sample of a BRICS country during the period 1992 to 2013. The empirical estimation obtained by using a GMM method showed that the N-shaped curve was found in the relation between income and pollution mitigation. Furthermore, Gill et al. (2019) studied the EKC hypothesis by analyzing the relationship between financial development and environmental warming in Malaysia over the period

1970–2016. The empirical findings showed that financial development has a negative impact on the environmental degradation.

Concentrating on EU countries, Acaravci and Ozturk (2010) achieve an ARDL model on the validation of the EKC hypothesis for nineteen European countries. Ang (2007) examined the case of France and confirmed the inverted U-shaped environmental Kuznets curve hypothesis. Friedl and Getzner (2003) analyzed the relationship between environmental mitigation and economic development in Austria when the Kyoto protocol was implemented. The empirical findings show the existence of the N-shaped EKC hypothesis. Lazăr et al. (2019) confirmed an inverted N and inverted U between climate change mitigation and economic growth in Central and Eastern European countries. Likewise, Chen et al. (2019) considered the EKC hypothesis for sixteen Central and Eastern European countries (CEECs) using the GMM model. Mert et al. (2019) appointed that the existence of the EKC hypothesis is resolved by the meaning of renewable energy consumption in 26 European countries.

Oil price and carbon dioxide emissions

Oil prices vary according to the exports and imports of countries and the political and economic state of each country. Some researchers have studied the relationships among economic growth, energy consumption, and carbon dioxide emissions without considering oil prices. For example, Shahbaz et al. (2017) showed that energy consumption has an important impact on CO₂ emissions, but Australia struggles with emissions due to globalization. Halkos and Paizanos (2013) investigated the impact of government spending on the environment, where the direct effect was significant in terms of CO₂ pollution. In 2016, these scholars studied the effect of fiscal policy on CO₂ emissions. The results showed that a deficit-financed tax cut leads to an increase in consumption-generated CO₂ emissions. Moreover, Ali et al. (2016) examined the impacts of the relationships among economic growth, energy consumption, and trade openness on CO₂ emissions in Nigeria. The results showed that urbanization has no significant impact on CO₂ emissions due to lower incomes in the country. Ali et al. (2017) examined the impacts of real GDP per capita, trade openness, and energy consumption on carbon dioxide emissions by applying an ARDL model. The results showed that the environmental Kuznets curve hypothesis could be applied in Malaysia. In addition, Cetin et al. (2018) studied the impacts of economic growth, energy consumption, trade openness, and financial development on carbon dioxide emissions. The results resorted that carbon emissions are determined by different variables, and the environmental Kuznets curve is valid for Turkey. Similarly, Ehigiamusoe and Lean (2019) used panel

data from 122 countries to investigate the impacts of economic growth, energy consumption, and financial development on carbon dioxide emissions. They found that energy consumption increases CO₂, and a low level of income and financial development decrease environmental quality. Li et al. (2020) examined the impact of energy prices on CO₂ emissions in China. They identified a significant negative impact of the energy price on environmental degradation.

Some studies have added oil prices because of their role in the economy. Among these studies, Bjerkholt and Niculescu (2004) showed that the size of oil export receipts influences the performance of economic factors. Villafuerte and Lopez-Murphy (2009) stated that a reduction in oil prices led financing needs in the future. Moreover, Fuinhas and Marques (2013) used an ARDL model to study the causality between energy consumption and economic growth for Algeria and Egypt. They found a positive elasticity for oil price and energy for Egypt and a negative relationship for Algeria. Furthermore, Wong et al. (2013) estimated the elasticities of energy consumption and energy R&D to changes in oil prices and income. They applied the NPAM model for 20 OECD countries in which their result reported a positive income elasticity for oil and gas and negative income elasticity for coal consumption. Additionally, Zhang et al. (2014) investigated the relationship between an increase in oil prices and companies' behavior of carbon emission reduction. They found that the impact of oil prices on companies' carbon reduction behavior is uncertain. Alshehry and Belloumi (2015) explored the causal interaction between energy price, energy consumption, and economic activity. The results showed the existence of unidimensional causality from energy prices to economic growth and CO₂ emissions. Then, the increase in energy consumption may increase CO₂ emissions but not economic growth. Saboori et al. (2016) used oil consumption, oil price, labor, and capital to examine the environmental quality curve hypothesis for 10 OPEC countries by applying the ARDL model. They found that oil prices reduce pollution. Countries must reduce the consumption of fossil fuel energy because it is the source of pollution. In addition, Sadorsky (2009) applied panel cointegration approach for an empirical model of renewable energy consumption for the G7 countries. The estimated results showed that the increase in oil prices has a negative impact on renewable energy consumption. Also, Acar (2017) examined the causal relationship between crude oil prices, CO₂ emissions, and energy consumption, where oil resources have a significant effect on the economy. Nwani (2017) investigated the causal relationship between crude oil prices, CO₂ emissions, and energy consumption in Ecuador. He showed that long-term and short-term effects exist and that crude oil prices have positive and statistically significant effects on CO₂ emissions and energy consumption. Higher oil prices increase energy consumption, environmental deterioration, and financial development. Moreover,

Boufateh (2019) examines the environmental Kuznets curve by considering the asymmetry of the effect of oil price on CO₂ emissions by applying the nonlinear ARDL approach. The results reported that positive and negative fluctuations in crude oil prices exert influence on CO₂ emissions in the USA and China. Agbanike et al. (2019) proved that CO₂ emissions exert a negative effect on economic growth in the oil-rich economy by considering a causal interaction between oil price, energy consumption, and carbon dioxide emissions in Venezuela. Mensah et al. (2019a, b) investigated the causal relationship with economic growth, carbon emissions, fossil fuel energy, and oil price for 22 African countries. The findings resorted the existence of a unilateral cause from oil prices to carbon emissions, economic growth, and energy consumption by applying a panel ARDL estimation model. Then, the study of Faik Bilgili et al. (2020) showed the effect of low and high oil prices on CO₂ emissions in China. This research affirmed the results found, where oil prices have a negative effect on CO₂ emissions in the 1960–2014 period. Accordingly, the authorities of China attempted to reduce CO₂ emissions.

Model, data, and methodology

Model

Based on the literature review presented above, this article used crude oil price to quantitatively measure oil rent to assess the impact of the COVID-19 shock on carbon emissions and economic growth in the Kingdom of Saudi Arabia, test the validity of the N-shaped EKC hypothesis, and examine the effect of the potential asymmetric reaction of oil price on carbon dioxide emissions, real GDP, and oil rent.

Based on the theory of the N-shaped environmental Kuznets curve, the empirical model is described as follows (Grossman and Krueger 1991; Panayotou 1997; De Bruyn et al. (1998); Stern 2004):

$$\text{Model 1 : } CO_{2t} = \alpha_0 + \alpha_1 GDP_t + \alpha_2 GDP_t^2 + \alpha_3 GDP_t^3 + \alpha_4 OILRENT_t + \alpha_5 OILP_t + \varepsilon_t \quad (1)$$

CO₂ refers to carbon dioxide emissions and measured by metric tons per capita, and GDP is the real income calculated in constant 2010 US\$; OILRENT indicates the difference between the value of crude oil production at world prices and total costs of production in % of GDP; OILP represents the spot crude oil prices selected from West Texas Intermediate (WTI) data, where α_0 is an intercept, t indicates time, α_1 , α_2 , α_3 , α_4 , and α_5 are the regression coefficients, and ε_t is the error term. Owing to the sign of the coefficients of different independent variables related to real GDP, the environmental

Kuznets curve will assume various styles (Balsalobre Lorente and Álvarez-Herranz 2016):

- If $\alpha_1 = \alpha_2 = \alpha_3 = 0$, no linkage exists between environmental quality and economic growth.
- If $\alpha_1 > 0$ and $\alpha_2 = \alpha_3 = 0$, then the increase in real GDP leads to environmental degradation.
- If $\alpha_1 < 0$ and $\alpha_2 = \alpha_3 = 0$, then the decrease in real GDP leads to environmental degradation.
- If $\alpha_1 < 0$ and $\alpha_2 > 0$ and $\alpha_3 = 0$, there will be a U-shaped relationship between environmental degradation and economic growth.
- If $\alpha_1 > 0$ and $\alpha_2 < 0$ and $\alpha_3 = 0$, we will see the standard inverted U-shaped EKC.
- If $\alpha_1 > 0$ and $\alpha_2 < 0$ and $\alpha_3 > 0$, there will be an N-shaped relationship between environmental degradation and economic growth.
- If $\alpha_1 < 0$ and $\alpha_2 > 0$ and $\alpha_3 < 0$, there will be an inverted N-shaped relationship between environmental deterioration and economic growth.

We attempt to investigate the relationships between economic growth and carbon dioxide emissions shaping the behavior of GDP and environmental quality. The volatility of both variables OILRENT and OILP would cause such fluctuations in the N-shaped EKC.

This survey states that OILRENT and OILP have not only a direct incidence of environmental deterioration but also an indirect moderating effect (ME) in the N-shaped EKC. This ME is tested by introducing interaction terms between GDP and OILRENT and OILP, between GDP^2 and OILRENT and OILP, and between GDP^3 and OILRENT and OILP.

First, the interaction term between GDP and OILRENT and OILP is expected to highlight the moderating role of OILRENT and OILP in the relationship between economic growth and environmental quality.

Second, the interaction term between GDP^2 and OILRENT and OILP is expected to highlight the moderating role of OILRENT and OILP in the relationship between quadratic GDP and environmental deterioration.

Third, the interaction term between GDP^3 and OILRENT and OILP is expected to highlight the moderating role of OILRENT and OILP in the relationship between cubic GDP and environmental degradation.

The restraining effects of the relationship between both variables (OILRENT and OILP) and GDP, GDP^2 , and GDP^3 are tested by the interaction terms. The interaction terms used in different models are expected to be statistically significant to confirm the existence of such moderating roles. Thus, the second model is stated as follows:

$$\text{Model 2 : } CO_{2t} = f(GDP_t, GDP_t^2, GDP_t^3, OILRENT_t, OILP_t, OILRENT_t * GDP_t, OILRENT_t * GDP_t^2, OILRENT_t * GDP_t^3, OILP_t * GDP_t, OILP_t * GDP_t^2, OILP_t * GDP_t^3) \quad (2)$$

To conserve the degree of freedom and address the multicollinearity issue, we separate Model 2 into three sub-models as follows: Model 2a:

$$CO_{2t} = f(GDP_t, GDP_t^2, GDP_t^3, OILRENT_t, OILP_t, OILRENT_t * GDP_t, OILP_t * GDP_t) \quad (2a)$$

Model 2b:

$$CO_{2t} = f(GDP_t, GDP_t^2, GDP_t^3, OILRENT_t, OILP_t, OILRENT_t * GDP_t^2, OILP_t * GDP_t^2) \quad (2b)$$

Model 2c:

$$CO_{2t} = f(GDP_t, GDP_t^2, GDP_t^3, OILRENT_t, OILP_t, OILRENT_t * GDP_t^3, OILP_t * GDP_t^3) \quad (2c)$$

The interference in the relationship between oil rent, oil price, and gross domestic product (GDP) highlights the modest effect of OILRENT and OILP on the relationship between environmental degradation and economic growth. The total effect of both variables (OILRENT and OILP) can arise by

considering the partial derivatives of carbon dioxide emissions with respect to the real GDP (Model 2a).

$$\begin{aligned} \partial CO_{2t} / \partial GDP_t &= \alpha_1 + 2\alpha_2 GDP_t + 3\alpha_3 GDP_t^2 \\ &+ \alpha_6 OILRENT_t + \alpha_7 OILP_t \end{aligned} \quad (2a1)$$

Equation (2a1) indicates that the marginal effect of the real GDP on environmental degradation mitigation changes with OILRENT and OILP. A positive sign of both coefficients of the composite variables (OILRENT and OILP) means that an expansion in oil rent and oil price would reinforce the effect of the real GDP on environmental degradation when α_1 has a positive sign and GDP is presumed to be constant.

The interference between oil rent, oil price, and GDP square refers to the modest effect of OILRENT and OILP on the relationship between environmental degradation and the GDP quadratic. The total effect of both variables (OILRENT and OILP) can arise by considering the partial derivatives of carbon dioxide emissions with respect to the GDP quadratic (Model 2b).

$$\partial CO_{2t} / \partial GDP_t^2 = \frac{\alpha_1}{2GDP_t} + 2\alpha_2 + 3\alpha_3 GDP_t + \alpha_6 OILRENT_t + \alpha_7 OILP_t \quad (2b1)$$

Equation (2b1) indicates that the marginal effect of GDP^2 on environmental degradation mitigation changes with OILRENT and OILP. A positive sign of both coefficients of the composite variables (OILRENT and OILP) indicates that an increase in oil rent and oil price would weaken the negative effect of GDP^2 on environmental degradation when α_2 has a negative sign and GDP is presumed to be constant.

The interference between oil rent, oil price, and GDP^3 refers to the modest effect of OILRENT and OILP on the relationship between environmental degradation and GDP^3 . The total effect of both variables (OILRENT and OILP) can arise by considering the partial derivatives of carbon dioxide emissions with respect to GDP^3 (Model 2c).

$$\partial CO_{2t} / \partial GDP_t^3 = \frac{\alpha_1}{3GDP_t^2} + \frac{\alpha_2}{2GDP_t} + \alpha_3 + \alpha_6 OILRENT_t + \alpha_7 OILP_t \quad (2c1)$$

Equation (2c1) indicates that the marginal effect of GDP^3 on environmental degradation mitigation changes with OILRENT and OILP. A positive sign of both coefficients of the composite variables (OILRENT and OILP) indicates that an increase in oil rent and oil price would weaken the positive effect of GDP^3 on environmental degradation when α_3 has a positive sign and GDP is presumed to be constant.

The interference term in these three models by the composite effects of OILRENT and OILP would be expected to have

significant and statistically significant effects. This research suggested that OILRENT and OILP are proxies of the increase in real GDP on CE in Model 2a, in addition to the proxy of the increase in GDP^2 on CE in model 2b and the proxy of the increase in GDP^3 on CE in Model 2c.

This study considers the COVID-19 crisis in the world including Saudi Arabia and uses crude oil price to quantitatively measure OILRENT and OILP to assess the impact of the COVID-19 shock on carbon emissions and economic growth in the Kingdom of Saudi Arabia by testing the validity of the N-shaped EKC hypothesis and examine the potential asymmetric effect of oil price on carbon dioxide emissions, real GDP and oil rent.

Oil prices play an important role in economic growth worldwide. However, any change in oil prices may negatively affect the oil rent of the revenue of oil-exporting countries (Mensah et al. 2019a, b), notably Saudi Arabia. This study tested the effects of the COVID-19 outbreak and suggested that such a disruption in oil price leads to a reduction in the consumption of oil by the COVID-19 shocks in 2019–2020. To minimize carbon dioxide emissions by testing the validity of the N-shaped EKC hypothesis and to examine the prospective asymmetric reaction of oil price on carbon dioxide emissions, real GDP and oil rent by COVID-19 shocks, we considered that the restraining effects of the pandemic on OILRENT, OILP, GDP, GDP^2 , and GDP^3 can be tested by the composite effects between variables. Then, the third model is presented as follows:

Model3 : CO_{2t}

$$= f(GDP_t * COVID-19_t, GDP_t^2 * COVID-19_t, GDP_t^3 * COVID-19_t, OILRENT_t * COVID-19_t, OILP_t * COVID-19_t) \quad (3)$$

To preserve the degree of freedom and address the multicollinearity issue, we divided Model 3 into three sub-models as follows:

$$\text{Model 3a : } CO_{2t} = f(GDP_t * COVID-19_t, GDP_t^2, GDP_t^3, OILRENT_t * COVID-19_t, OILP_t * COVID-19_t) \quad (3a)$$

$$\text{Model 3b : } CO_{2t} = f(GDP_t, GDP_t^2 * COVID-19_t, GDP_t^3, OILRENT_t * COVID-19_t, OILP_t * COVID-19_t) \quad (3b)$$

$$\text{Model 3c : } CO_{2t} = f(GDP_t, GDP_t^2, GDP_t^3 * COVID-19_t, OILRENT_t * COVID-19_t, OILP_t * COVID-19_t) \quad (3c)$$

Table 1 Descriptive statistics of the variables

	CE	GDP	OILP	OILRENT
Mean	2.695587	9.852108	3.255313	3.602670
Median	2.698174	9.879154	3.308241	3.571478
Maximum	2.969388	10.57521	4.590767	4.487125
Minimum	2.048999	2.806767	1.269761	2.839150
Std. dev.	0.206921	1.040652	0.830214	0.349818
Skewness	−0.703638	−6.219832	−0.593403	0.157081
Kurtosis	3.342796	42.88673	3.296116	2.738470
Jarque-Bera	4.458115	3709.605	3.179410	0.355079
Probability	0.107630	0.000000	0.203986	0.837328
Sum	137.4749	502.4575	166.0210	183.7362
Sum Sq. dev.	2.140807	54.14788	34.46273	6.118632
Observations	51	51	51	51

Data

Our data were obtained from World Development Indicators (2020) for the Kingdom of Saudi Arabia over the period 1970–2020. The main variables used in our tested models are CE, representing carbon emissions measured by metric tons per capita; GDP, representing the real income calculated in constant 2010 US\$; OILRENT, indicating the difference crude oil production at world prices and the total costs of production in % of the GDP; OILP, representing the spot crude oil prices selected from West Texas Intermediate (WTI) data; and COVID-19 shocks, representing the new global pandemic and taking the value one (1) over the period 1970–2018, and minus one (−1) during the outspreading pandemic period 2019–2020. It is important to mention that the variables CE, GDP, OILRENT, and OILP are transformed into their natural log form.

Table 1 presents the descriptive statistics of the variables: in the Kingdom of Saudi Arabia, the extreme value of CE is 2.96, GDP is 10.57, OILP is 4.59, and OILP is 4.48, but the lowest values of these variables are 2.048, 2.80, 1.26, and 2.83, respectively. These results highlight the asymmetry of the impacts of the oil price and COVID-19 shocks on all other variables (real GDP, oil rent and CE) during 2019–2020 period. The positive and negative components are determined by the cumulative function of the positive and negative shocks of the oil price in Saudi Arabia, Hatemi-J (2012). Time plots of the real GDP, CE, OILRENT, OILP, and the cumulative function of the positive and negative shocks (OILP⁺, OILP[−]) of oil price are presented in Fig. 1 (Table 2).

Unit root tests

We adopt three different approaches to test the long-run relationship among the variables: the autoregressive distributed lag (ARDL) and non-autoregressive distributed lag (NARDL) model. These ARDLs and NARDLs are applicable where all variables (CE, GDP, OILRENT, and OILP) used in the models are stationary at the level of the first difference or the mixing of both methods. To verify the integration order, the implication of any order if integration I(2) must be eliminated and the request of ARDL and the NARDL are limited in the variable integrated I(1). To evaluate the order of integration of the four variables CE, GDP, OILRENT, and OILP, conservative unit root tests use ADF (augmented Dickey and Fuller 1981), PP (Phillips and Perron 1988), KPSS (Kwiatkowski et al. 1992), and RES (Elliott et al. 1992).

The summarized results of all unit root tests are calculated using intercepts and trends at the level and in the first difference. The findings of all unit root tests show that none of the second-order integration I(2) variables needed to be included.

Table 2 Unit root tests: series at level and in the first difference

	ADF	PP		KPSS		RES	
	Intercept	Trend	Intercept	Trend	Intercept	Trend	Intercept Trend
CE	−3.582**	−3.962	−3.587**	−3.996*	0.668***	0.094* 21.096*	13.708*
ΔCE	−7.510***	−7.495***	−8.061***	−7.858***	0.148*	0.078* 2.996*	4.885*
GDP	−0.3796	−1.7917	−0.3687	−1.7919	0.575	0.0901 6.791	11.625*
ΔGDP	−5.272***	−5.433***	−5.352***	−7.366***	0.3276	0.1337 6.742	11.699*
OILRENT	−2.070	−2.707	−2.159	−2.788	0.267	0.086 3.406	10.074*
ΔOILRENT	−5.947***	−6.018***	−7.187***	−7.248***	0.188**	0.088 2.596	6.139
OILP	−2.589	−2.460	−2.578	−2.460	0.692*	0.073 30.075**	14.052*
ΔOILP	−7.782***	−8.028***	−7.782***	−8.099***	0.223	0.099 1.520	5.129

Notes: ADF augmented Dickey-Fuller, PP Phillips-Perron, KPSS Kwiatkowski-Phillips-Schmidt-Shin, RES Elliott-Rothenberg-Stock, Δ is the first difference operator

***, **, and *denote significance levels of 1%, 5%, and 10%, respectively

Fig. 1 Plots of CE, GDP, OILRNT, OILP, OILP⁺, and OILP⁻ represent the plot of the partial sum of positive and negative shocks

Table 3 presents the results of the structural break unit root test of the innovative outlier and additive outlier, showing that all variables do not have any problems of stationarity in the presence of the structural breaks in 1975, 1994, 2000, and 2003 (CE) at the level and 1975, 1994, and 2000 at the first difference; in 2009, 2013, and 2019 (GDP) at the level and in 2009, 2013, 2018, and 2019 at the first difference; in 1982 and 1998 (OILP) at the level and in 1981 and 1998 at the first difference; and in 2003 and 2014 (OILRNT) at the level and 1974 and 1981 at the first difference.

The structural break detected by OILP from 1981 to 1982 highlights the crude oil surplus caused by the drop in global demand in Saudi Arabia. Therefore, the energy crisis over the period 1981–1982 can explain the structural break detected by OILRNT in 1981. In addition, the structural break detected by the real GDP in Saudi Arabia in 2019 is explained by the COVID-19 crisis.

Bounds cointegration tests

In compliance with the results of the unit root test in the presence of structural breaks of the innovative outlier and additive outlier, our results show that all the variables used had any problems of stationarity in the presence of the structural breaks in the first difference with intercept and intercept and trend (Table 3). Bound cointegration tests can be used for all models to reveal the long-run relationship between CE, OILRNT, OILP, GDP, OILP⁺, OILP⁻, and COVID-19.

After calculating the Fisher statistic of the Wald test, if it is above the crucial bounds test of Pesaran et al. (2001) or Narayan (2005) tables at the 5% level of meaning, also, the null hypothesis of a no-long-run association between the dependent variable (CE) and independent variables (OILRNT, OILP, GDP, OILP⁺, OILP⁻, and COVID-19) is rejected. In addition, when the calculated F-statistics of all models are

Table 3 Unit root test with structural breaks (innovative outlier and additive outlier)

	Innovative outlier				Additive outlier			
	Level	t-statistic	break date	First difference	Level	t-statistic	break date	First difference
				Intercept				t-statistic
CE	–4.933465**	2003		–8.197377***	1975	–4.989257***	2003	–8.444289***
GDP	–2.254229	2019		–5.078436***	2019	–2.732371	2013	–13.81634***
OILRENT	–3.282041	2014		–7.447454***	1974	–3.375320	2014	–7.609149***
OILP	–3.635395	1998		–8.483038***	1981	–3.646943	1998	–8.664337***
				Intercept and Trend				
CE	–4.965273**	1994		–8.128838***	2000	–4.969584**	1994	–8.448449***
GDP	–2.236017	2018		–4.083180*	2018	–3.723287	2009	–5.176257**
OILRENT	–3.946982	2003		–7.412186***	1982	–4.081495*	2003	–7.412186***
OILP	–3.181250	1982		–9.068341***	1998	–3.349317	1982	–9.500953***

***, **, and *denote significance levels of 1%, 5%, and 10%, respectively

smaller than the critical value of bounds tests, then the null hypothesis of a no-long-run association between the dependent variable (CE) and independent variables (OILRENT, OILP, GDP, OILP+, OILP–, and COVID-19) is accepted.

All critical value Fisher tests of all models in Table 4 are smaller than the critical value of bounds tests, and then the null hypothesis of bounds cointegration test is rejected against the alternative hypothesis of the existing co-integration. Therefore, the long-run association between the dependent variable (CE) and independent variables (OILRENT, OILP, GDP, OILP+, OILP–, and COVID-19) is validated.

For the critical values for the bounds test of the co-integration of Narayan (2005) (case III: unrestricted intercept and no trend, $K=5$), the two critical values for 5% are 2.848 and 4.160 and for the 1% are 3.928 and 5.408. Therefore, the results of Table 4 confirm the long-run cointegration between

the dependent variable (CE) and independent variables because the F-statistics are significant at the 1% level.

Autoregressive distributed lag methodology (ARDL)

To demonstrate the short- and long-run relationship between the dependent variable (CE) and independent variables (OILRENT, OILP, GDP, and COVID-19), the methodology provides many econometric techniques, such as unit root tests of stationarity ADF (augmented Dickey and Fuller 1981), PP (Phillips and Perron 1988), KPSS (Kwiatkowski et al. 1992), and RES (Elliott et al. 1992). In addition, the unit root test in the presence of structural breaks of the innovative outlier and additive outlier shows that all variables used had any problems of stationarity in the presence of the structural breaks. Nevertheless, bounds cointegration tests are broadly used and claim that all variables are integrated in the same order in the first difference. Regardless of the form of the ARDL model used in this study, this approach accounts for the inherent heterogeneity effect in the data. Hence, applying the ARDL model ensures the elimination of serial correlations and endogeneity problems. Furthermore, the ARDL model is more appropriate for examining the short- and long-run relationships in the presence of $I(1)$ variables or variables with mixed order of integration not more than one ($I(1)$ and $I(0)$), except that the dependent variable should be $I(1)$.

Pesaran and Shin's (1998) methodology was used to study the dynamic short- and long-run association between the dependent variable (CE) and independent variables (OILRENT, OILP, and GDP). The ARDL is defined as follows:

Table 4 Results of bounds cointegration tests

Test statistic	Value	Signif.	I(0)	I(1)
F-statistic (Model 1)	4.527187	10%	1.81	2.93
F-statistic (Model 2a)	4.671282	5%	2.14	3.34
F-statistic (Model 2b)	4.671282	1%	2.82	4.21
F-statistic (Model 2c)	4.731972			
F-statistic (Model 3)	5.698128			
F-statistic (Model 3a)	4.546782			
F-statistic (Model 3b)	4.642503			
F-statistic (Model 3c)	7.566955			
F-statistic (Model 4)	5.976610			

F statistic=4.57, $K=5$

$$\begin{aligned}
 \Delta CO_{2t} = & \alpha_1 CO_{2t-1} + \alpha_2 GDP_{t-1} + \alpha_3 GDP_{t-1}^2 \\
 & + \alpha_4 GDP_{t-1}^3 + \alpha_5 OILRENT_{t-1} + \alpha_6 OILP_{t-1} \\
 & + \sum_{i=0}^p \alpha_7 \Delta CO_{2t-i} + \sum_{i=0}^q \alpha_8 \Delta GDP_{t-i} \\
 & + \sum_{i=0}^r \alpha_9 \Delta GDP_{t-i}^2 + \sum_{i=0}^s \alpha_{10} \Delta GDP_{t-i}^3 \\
 & + \sum_{i=0}^t \alpha_{11} \Delta OILRENT_{t-i} + \sum_{i=0}^u \alpha_{12} \Delta OILP_{t-i} \\
 & + \varepsilon_t
 \end{aligned} \tag{4}$$

$$\begin{aligned}
 \Delta CO_{2t} = & \beta_1 CO_{2t-1} + \beta_2 GDP_{t-1} + \beta_3 GDP_{t-1}^2 + \beta_4 GDP_{t-1}^3 + \beta_5 (OILRENT * GDP)_{t-1} \\
 & + \beta_6 (OILP * GDP)_{t-1} + \sum_{i=0}^p \beta_7 \Delta CO_{2t-i} + \sum_{i=0}^q \beta_8 \Delta GDP_{t-i} + \sum_{i=0}^r \beta_9 \Delta GDP_{t-i}^2 + \sum_{i=0}^s \beta_{10} \Delta GDP_{t-i}^3 + \\
 & + \sum_{i=0}^t \beta_{11} \Delta (OILRENT * GDP)_{t-i} + \sum_{i=0}^u \beta_{12} \Delta (OILP * GDP)_{t-i} + K_t
 \end{aligned} \tag{5}$$

$$\begin{aligned}
 \Delta CO_{2t} = & \omega_1 CO_{2t-1} + \omega_2 GDP_{t-1} + \omega_3 GDP_{t-1}^2 + \omega_4 GDP_{t-1}^3 + \omega_5 (OILRENT * GDP^2)_{t-1} \\
 & + \omega_6 (OILP * GDP^2)_{t-1} + \sum_{i=0}^p \omega_7 \Delta CO_{2t-i} + \sum_{i=0}^q \omega_8 \Delta GDP_{t-i} + \sum_{i=0}^r \omega_9 \Delta GDP_{t-i}^2 \\
 & + \sum_{i=0}^s \omega_{10} \Delta GDP_{t-i}^3 + \sum_{i=0}^t \omega_{11} \Delta (OILRENT * GDP^2)_{t-i} + \sum_{i=0}^u \omega_{12} \Delta (OILP * GDP^2)_{t-i} + h_t
 \end{aligned} \tag{6}$$

$$\begin{aligned}
 \Delta CO_{2t} = & \rho_1 CO_{2t-1} + \rho_2 GDP_{t-1} + \rho_3 GDP_{t-1}^2 + \rho_4 GDP_{t-1}^3 + \rho_5 (OILRENT * GDP^3)_{t-1} \\
 & + \rho_6 (OILP * GDP^3)_{t-1} + \sum_{i=0}^p \rho_7 \Delta CO_{2t-i} + \sum_{i=0}^q \rho_8 \Delta GDP_{t-i} + \sum_{i=0}^r \rho_9 \Delta GDP_{t-i}^2 \\
 & + \sum_{i=0}^s \rho_{10} \Delta GDP_{t-i}^3 + \sum_{i=0}^t \rho_{11} \Delta (OILRENT * GDP^3)_{t-i} + \sum_{i=0}^u \rho_{12} \Delta (OILP * GDP^3)_{t-i} + v_t
 \end{aligned} \tag{7}$$

In addition, the effects of the COVID-19 pandemic on environmental quality in the KSA and the validity of the N-shaped EKC hypothesis are tested by incorporating the interaction terms of the COVID-19 pandemic outbreak with OILRENT, OILP, GDP, GDP², and GDP³.

Thus, the ARDL model as follows:

$$\begin{aligned}\Delta CO_{2t} = & \beta_1 CO_{2t-1} + \beta_2 (GDP * COVID-19)_{t-1} \\ & + \beta_3 GDP_{t-1}^2 + \beta_4 GDP_{t-1}^3 \\ & + \beta_5 (OILRENT * COVID-19)_{t-1} \\ & + \beta_6 (OILP * COVID-19)_{t-1} + \sum_{i=0}^p \beta_7 \Delta CO_{2t-i} \\ & + \sum_{i=0}^q \beta_8 \Delta (GDP * COVID-19)_{t-i} \\ & + \sum_{i=0}^r \beta_9 \Delta GDP_{t-i}^2 + \sum_{i=0}^s \beta_{10} \Delta GDP_{t-i}^3 \\ & + \sum_{i=0}^t \beta_{11} \Delta (OILRENT * COVID-19)_{t-i} \\ & + \sum_{i=0}^u \beta_{12} \Delta (OILP * COVID-19)_{t-i} + K_t\end{aligned}\quad (8)$$

$$\begin{aligned}\Delta CO_{2t} = & \omega_1 CO_{2t-1} + \omega_2 GDP_{t-1} + \omega_3 (GDP^2 * COVID-19)_{t-1} + \omega_4 GDP_{t-1}^3 + \omega_5 (OILRENT * GDP^2)_{t-1} \\ & + \omega_6 (OILP * GDP^2)_{t-1} + \sum_{i=0}^p \omega_7 \Delta CO_{2t-i} + \sum_{i=0}^q \omega_8 \Delta GDP_{t-i} + \sum_{i=0}^r \omega_9 \Delta (GDP^2 * COVID-19)_{t-i} \\ & + \sum_{i=0}^s \omega_{10} \Delta GDP_{t-i}^3 + \sum_{i=0}^t \omega_{11} \Delta (OILRENT * GDP^2)_{t-i} + \sum_{i=0}^u \omega_{12} \Delta (OILP * GDP^2)_{t-i} + h_t\end{aligned}\quad (9)$$

$$\begin{aligned}\Delta CO_{2t} = & \rho_1 CO_{2t-1} + \rho_2 GDP_{t-1} + \rho_3 GDP_{t-1}^2 + \rho_4 (GDP^3 * COVID-19)_{t-1} + \rho_5 (OILRENT * GDP^3)_{t-1} \\ & + \rho_6 (OILP * GDP^2)_{t-1} + \sum_{i=0}^p \rho_7 \Delta CO_{2t-i} + \sum_{i=0}^q \rho_8 \Delta GDP_{t-i} + \sum_{i=0}^r \rho_9 \Delta GDP_{t-i}^2 \\ & + \sum_{i=0}^s \rho_{10} \Delta (GDP^3 * COVID-19)_{t-i} + \sum_{i=0}^t \rho_{11} \Delta (OILRENT * GDP^2)_{t-i} + \sum_{i=0}^u \rho_{12} \Delta (OILP * GDP^2)_{t-i} + v_t\end{aligned}\quad (10)$$

The coefficient terms of the level ($\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6$), ($\omega_1, \omega_2, \omega_3, \omega_4, \omega_5, \omega_6$), and ($\rho_1, \rho_2, \rho_3, \rho_4, \rho_5, \rho_6$) reflect long-run dynamics, while the coefficient terms in the first difference ($\beta_7, \beta_8, \beta_9, \beta_{10}, \beta_{11}, \beta_{12}$), ($\omega_7, \omega_8, \omega_9, \omega_{10}, \omega_{11}, \omega_{12}$), and ($\rho_7, \rho_8, \rho_9, \rho_{10}, \rho_{11}, \rho_{12}$) reflect short-run effects. Here, (K_t, h_t and v_t) denotes the error term, and Δ denotes the first difference operator.

The long-run slope (elasticity) coefficients of GDP, GDP^2 , GDP^3 , OILRENT, and OILP are computed as $\frac{-\beta_l}{\beta_1}, \frac{-\omega_l}{\omega_1}$ and $\frac{-\rho_l}{\rho_1}$ for $l=2,3,4,5,6$. The lagged variables ($p, q, r, s, t, \text{ and } u$) are determined based on either the Akaike information criterion (AIC) or Schwarz Bayesian criterion (S.B.C). Using a Wald test, the presence of cointegration relationships for models is tested by the following:

$$\begin{cases} H_0 : \beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = \beta_6 = 0 \text{ (absence of long-run relationship)} \\ H_1 : \beta_1 \neq \beta_2 \neq \beta_3 \neq \beta_4 \neq \beta_5 \neq \beta_6 \neq 0 \text{ (presence of long-run relationship)} \end{cases}$$

$$\begin{cases} H_0 : \omega_1 = \omega_2 = \omega_3 = \omega_4 = \omega_5 = \omega_6 = 0 \text{ (absence of long-run relationship)} \\ H_1 : \omega_1 \neq \omega_2 \neq \omega_3 \neq \omega_4 \neq \omega_5 \neq \omega_6 \neq 0 \text{ (presence of long-run relationship)} \end{cases}$$

$$\begin{cases} H_0 : \rho_1 = \rho_2 = \rho_3 = \rho_4 = \rho_5 = \rho_6 = 0 \text{ (absence of long-run relationship)} \\ H_1 : \rho_1 \neq \rho_2 \neq \rho_3 \neq \rho_4 \neq \rho_5 \neq \rho_6 \neq 0 \text{ (presence of long-run relationship)} \end{cases}$$

Furthermore, we compare the calculated F-statistics of the three models with Narayan's (2005) critical value. If the Fisher statistic of the Wald test is above the crucial bound proposed by Narayan (2005), the null hypothesis that no long-run association exists between the dependent variable (CE) and independent variables is rejected. When the calculated F-statistics of all models are smaller than the critical value of the bound tests, then the null hypothesis that no

long-run association exists between the dependent variable (CE) and independent variables is accepted.

Asymmetric ARDL (nonlinear autoregressive distributed lag methodology: NARDL)

To demonstrate the symmetric and asymmetric effect of the oil price in the presence of the COVID-19 outbreak on the environmental quality in the KSA, we use the methodology of Shin et al. (2014) and adopt a non-autoregressive distributed lag model. Unlike the symmetric case, this version of the ARDL referred to as a nonlinear ARDL allows for the asymmetric response of CO₂ emissions to oil prices in the presence of the coronavirus crisis. In other words, under this scenario, the increase and decrease in the OILP levels in the presence of the COVID-19 pandemic are not expected to have identical effects on CO₂ emissions. In accordance with Shin et al. (2014), the asymmetric version of Eq. (2) that considers the combined shocks of the COVID-19 and oil volatility shocks can be written in the following form:

$$\begin{aligned} \Delta CO_{2t} = & \Phi_1 CO_{t-1} + \Phi_2 GDP_{t-1} + \Phi_3 GDP_{t-1}^2 \\ & + \Phi_4 GDP_{t-1}^3 + \Phi_5 OILRENT_{t-1} \\ & + \Phi_6 (COVID-19 * OILP^-)_{t-1} \\ & + \Phi_7 (COVID-19 * OILP^+)_{t-1} \\ & + \sum_{i=0}^p \Phi_8 \Delta CO_{2t-i} + \sum_{i=0}^q \Phi_9 \Delta GDP_{t-i} \\ & + \sum_{i=0}^r \Phi_{10} \Delta GDP_{t-i}^2 + \sum_{i=0}^s \Phi_{11} \Delta GDP_{t-i}^3 \\ & + \sum_{i=0}^t \Phi_{12} \Delta OILRENT_{t-i} \\ & + \sum_{i=0}^u \Phi_{13} (COVID-19 * OILP^-)_{t-i} \\ & + \sum_{i=0}^u \Phi_{14} (COVID-19 * OILP^+)_{t-i} + \pi_t \end{aligned} \quad (11)$$

where $OILP^+$ and $OILP^-$ denote the positive and negative partial sum decompositions of the oil price change, respectively, and are computed as follows:

$$OILP^+ = \sum_{i=1}^t \Delta OILP_i^+ = \sum_{i=1}^t \max(\Delta OILP_i, 0) \quad (11a)$$

$$OILP^- = \sum_{i=1}^t \Delta OILP_i^- = \sum_{i=1}^t \min(\Delta OILP_i, 0) \quad (11b)$$

The long-run coefficients of $OILP^+$ and $OILP^-$ are computed as Φ_7/Φ_1 and Φ_6/Φ_1 , respectively. Using a Wald test, the long-run relationship is identified when the null hypothesis is rejected. $H_0: \Phi_1 = \Phi_2 = \Phi_3 = \Phi_4 = \Phi_5 = \Phi_6 = \Phi_7 = 0$.

Through a Wald test, the existence of a long-run asymmetric impact of oil price on CO₂ emissions in the presence of the COVID-19 outbreak is examined by testing $H_0: \Phi_6 = \Phi_7$ against the alternative hypothesis $H_1: \Phi_6 \neq \Phi_7$.

Likewise, the existence of a short-run asymmetric impact of oil prices on CO₂ emissions in the presence of the COVID-19 pandemic is examined by testing $H_0: \Phi_{13} = \Phi_{14}$ against the alternative hypothesis $H_1: \Phi_{13} \neq \Phi_{14}$.

Results and discussion

Autoregressive distributed lag methodology (ARDL)

Table 5 presents the short- and long-run results of the ARDL models. Our findings indicate that when Model 1 is employed, the results show proof of the N-shaped EKC. The coefficients of both variables GDP and GDP³ are negative and statistically significant; in addition, the sign of the coefficient of the quadratic shape of the real GDP is positive and statistically significant. These results show that an inverted N-shaped EKC exists in Saudi Arabia.

The results of Model 1 show a negative and significant relationship between oil rent (OILRENT) and carbon dioxide emissions in the long run. These results indicate that in the KSA, an increase of 1% in the oil rent (OILRENT) will lead to the mitigation of environmental degradation by 0.204%. Oil rents are the difference between the value of crude oil production at world prices and the total cost of production. The proxy (OILRENT) is highly sensitive to changes in oil prices worldwide, and any changes in crude oil prices lead to a significant change in the oil rent in the KSA. The oil price (OILP) is positive and statistically significant in the long run; the results indicate that an increase of 1% in the oil price (OILP) will lead to an increase in CE by 0.19% at the 1% level of significance. In addition, the positive sign of the coefficient of OILP elasticity in all models proves that in the KSA, the OILP is an important indicator of an increase in energy use and fluctuations in environmental degradation (Nwani 2017). The fact that this phenomenon occurs in Saudi Arabia indicates that it is worth exploring this phenomenon in oil-exporting countries. In the KSA, the actual energy price is less than the international market price, which leads to an increase in energy consumption and an increase in carbon dioxide emissions. The major factor in the decline in oil prices is government grants (Li et al. 2019). The results of Models (1, 2a, 2b, and 2c) for the short term indicate that the short-term elasticity of carbon dioxide emissions has decreased (0.45–0.26: Model 1); this decrease reflects the response to the variation in the market oil price in the short term. The N-shaped EKC hypothesis is not validated in the KSA.

In Models 2a, 2b, and 2c, the interaction terms between oil price and level and quadratic and cubic economic growth have

Table 5 Linear ARDL estimation and diagnostic checks (CE-dependent variable)

Long-run estimates Variable	Model1 ARDL Coef.	(3, 0, 1, 3, 0, 0) Prob.	Model2a ARDL Coef.	(3, 0, 1, 3, 0, 0) Prob.	Model2b ARDL Coef.	(3, 0, 1, 3, 0, 0) Prob.	Model2c ARDL Coef.	(3, 0, 1, 3, 0, 0) Prob.
GDP	-9.805307**	0.0486	-9.728744	0.0468	-9.670249	0.0453	-9.627365	0.0440
GDP ²	1.989659**	0.0431	1.972662	0.0417	1.959101	0.0406	1.948489	0.0397
GDP ³	-0.098032**	0.0435	-0.097092	0.0425	-0.096315	0.0417	-0.095677	0.0412
OILP	0.193888***	0.0000	-	-	-	-	-	-
OILRENT	-0.204107*	0.0121	-	-	-	-	-	-
OILP*GDP	-	-	0.019366***	0.0000	-	-	-	-
OILRENT*GDP	-	-	-0.020500**	0.0108	-	-	-	-
OILP*GDP ²	-	-	-	-	0.001931***	0.0000	-	-
OILRENT*GDP ²	-	-	-	-	-0.002055***	0.0099	-	-
OILP*GDP ³	-	-	-	-	-	-	0.000192***	0.0000
OILRENT*GDP ³	-	-	-	-	-	-	-0.000206***	0.0092
Short-run estimates								
Δ (CE (-1))	0.251239*	0.0706	0.256143*	0.0652	0.260668*	0.0605	0.264629*	0.0566
Δ (CE (-2))	0.436326**	0.0017	0.441782**	0.0015	0.446854**	0.0013	0.451364**	0.0012
Δ (GDP ²)	0.983026***	0.0000	0.983422***	0.0000	0.985273***	0.0000	0.987204***	0.0000
Δ (GDP ³)	-0.037439***	0.0001	-0.037284***	0.0001	-0.037204***	0.0000	-0.037125***	0.0000
Δ (GDP ² (-1))	0.000190	0.7254	0.000203	0.7075	0.000216	0.6887	0.000229	0.6693
Δ (GDP ³ (-2))	-0.001329**	0.0202	-0.001326**	0.0201	-0.001324**	0.0199	-0.001322**	0.0196
ECT (-1)	-0.762489***	0.0000	-0.771689***	0.0000	-0.780026***	0.0000	-0.787172***	0.0000
Diagnostic test	F-statistic	Prob.	F-statistic	Prob.	F-statistic	Prob.	F-statistic	Prob.
RESET test	6.346633	0.0165	5.998225	0.0195	5.598836	0.0236	5.157839	0.0294
Normality test	3.801475	0.149458	3.801475	0.149458	4.408060	0.110358	4.804681	0.090506
LM test:	0.692872	0.5071	4.073957	0.13042	0.853113	0.4350	0.942399	0.3996
Heteroskedasticity test	1.226092	0.3049	1.190018	0.3278	1.147920	0.3561	1.101240	0.3895

 Δ is the first difference operator

***, **, and * denote significance levels of 1%, 5%, and 10%, respectively

a positive and statistically significant effect on enhancing the relationship between economic growth and environmental quality. Moreover, all coefficients of the level, quadratic, and cubic GDP indicate elasticity and are statistically significant. In models 2a, 2b, and 2c, the interaction term between oil rent and level and quadratic and cubic economic growth has a negative and statistically significant effect on the relationship between economic growth and environmental degradation in the KSA. Moreover, all coefficients of the level, quadratic and cubic GDP indicate inelasticity and are statistically significant. The effect of economic growth on environmental quality appears to be stronger in the models with the interaction term that indicates dependency on natural resources (oil rent) in the KSA prevents the N-shaped EKC from re-inverting.

As shown in Table 1, the F-statistic values of the bound cointegration tests in Models 1, 2a, 2b, and 2c (4.527187, 4.671282, 4.671282, and 4.731972) are higher than the upper critical value of the bound tests proposed by Narayan (2005) (Table 4). It follows that the hypothesis regarding the existence of long-run cointegration between environmental quality and oil price, oil rent, and real GDP variables is confirmed. The lagged error correction terms $ECT(-1)$ are negative and statistically significant (-0.474817 , -0.780235 , -0.787490 , and -0.544065), which confirms the long-run association proposed by Pesaran et al. (2001) and indicates that any disequilibrium appearing in Models (1, 2a, 2b, and 2c) can be adjusted (0.47%, 0.78%, 0.787%, and 0.544%, respectively). The choice of the optimal lag length in Models 1, 2a, 2b, and 2c using the first difference of variables is based on the Akaike information criterion (AIC) and the Schwarz information criterion (SIC). The estimation models include diagnostic tests, such as the Breusch-Godfrey serial correlation (LM test), normality tests, and the heteroskedasticity test of Breusch-Pagan-Godfrey, and stability tests, such as the Ramsey RESET test and CUSUM test and the CUSUM of squares test (Brown et al. 1975). These tests indicate that there are no problems related to serial correlation and heteroskedasticity in the residuals and that the results are normally distributed; in addition, all models are stable.

Table 6 presents the short- and long-run assessment results of the ARDL models that consider the COVID-19 shock. The results of Model 3 provide proof of the N-shaped EKC. The coefficients of both composite variables ($GDP \times COVID-19$) and ($GDP^3 \times COVID-19$) are negative and statistically significant. The sign of the coefficient of the quadratic shape of the composite real GDP with COVID-19 is positive and statistically significant in the results of Models (3), (3a), and (3c) and is not validated in model (3b). The results of Models (3), (3a), and (3c) show an inverted N-shaped EKC in Saudi Arabia in the long run.

The results of Model3 indicate a negative and significant relationship between oil rent (OILRENT) and carbon dioxide emissions in the long run and that an increase of 1% in the oil

rent (OILRENT) will lead to the mitigation of environmental degradation by 0.21% (Adedoyin et al. 2020), meaning that in the KSA, the COVID-19 shock will lead to the mitigation of carbon dioxide emissions by 0.05%. The coefficient of oil price (OILP) is positive and statistically significant in the long run; in the presence of the COVID-19 pandemic, an increase of 1% in the oil price (OILP) will lead to an increase in CE by 0.22% at the 1% level of significance. The positive sign of the coefficient of OILP elasticity in all models proves that in the KSA, the OILP is an important indicator of an increase in energy use and fluctuations in environmental degradation. This result for Saudi Arabia should be confirmed for oil-exporting countries. In the KSA, the actual energy price is less than the international market price due to the coronavirus crisis, which led to an increase in energy consumption, increasing carbon dioxide emissions; however, the major factor in the decline in oil prices is government grants (Li et al. 2019). The results of Models 3, 3a, 3b, and 3c for the short term indicate that the elasticity of carbon dioxide emissions has decreased (0.45–0.26; Model 3a), and this decrease is responsive to the variation in the market oil price in the short term. The N-shaped EKC hypothesis is not validated for the KSA.

As shown in Table 6, the F-statistic values for the bound cointegration tests conducted for Models 3, 3a, 3b, and 3c are higher than the upper critical value of bound tests proposed by Narayan (2005) Table 4. It follows that the hypothesis regarding the existence of long-run cointegration between CE and the independent variables is confirmed. The lagged error correction term ($ECT(-1)$) is negative and statistically significant, confirming the long-run association proposed by Pesaran et al. (2001). Any disequilibrium appearing in Models 3, 3a, 3b, and 3c is adjusted (by 0.47%, 0.78%, 0.787% and 0.544%). The choice of the optimal lag length in Models 3, 3a, 3b, and 3c for the first differences of variables is determined based on the Akaike information criterion (AIC) and the Schwarz information criterion (SIC).

The estimation models incorporate diagnostic tests, such as the Breusch-Godfrey serial correlation LM test, normality tests, and heteroskedasticity test of Breusch-Pagan-Godfrey, and stability tests, such as the Ramsey RESET test and CUSUM test and CUSUM of squares test (Brown et al. 1975); these tests indicate that there are no problems of serial correlation and heteroskedasticity touching residuals and the results are normally distributed. All models are stable.

Non-autoregressive distributed lag methodology (NARDL)

Table 7 presents the short- and long-run assessment results of the NARDL models considering the COVID-19 shock. The results of Model 11 provide proof of the N-shaped EKC. The coefficients of both composite variables GDP and GDP^3 are

Table 6 Linear ARDL estimation and diagnostic checks (CE-dependent variable)

Long-run estimates Variable	Model3 ARDL Coef.	(1, 0, 1, 1, 0, 0) Prob.	Model3a ARDL Coef.	(3, 0, 3, 3, 1, 0) Prob.	Model3b ARDL Coef.	(3, 1, 1, 1, 1, 0) Prob.	Model3c ARDL Coef.	(1, 0, 0, 1, 1, 0) Prob.
GDP	-	-	-	-	-0.373920	0.3402	-0.155174	0.3112
GDP ²	-	-	0.046921***	0.0000	-	-	0.072438***	0.0006
GDP ³	-	-	-0.002011**	0.0248	-0.005875	0.1151	-	-
GDP*COVID-19	-3.377948***	0.0000	0.022319*	0.4322	-	-	-	-
GDP ² *COVID-19	0.714190***	0.0000	-	-	0.123465	0.1060	-	-
GDP ³ *COVID-19	-0.034834***	0.0000	-	-	-	-	-0.003057***	0.0002
OILP*COVID-19	0.217214***	0.0000	0.222088***	0.0000	0.237918***	0.0000	0.226469***	0.0000
OILRENT*COVID-19	-0.211261*	0.1017	-0.255849**	0.0015	-0.221618**	0.0046	-0.179069*	0.0934
Short-run estimates								
Δ (GDP ² *COVID-19)	0.243922***	0.0000	-	-	-	-	-	-
Δ (GDP ³ *COVID-19)	-0.008373***	0.0006	-	-	-	-	-	-
Δ (CE (-1))	-	-	0.260496*	0.0637	0.256617	0.0443	-	-
Δ (CE (-2))	-	-	0.457140***	0.0011	0.336386	0.0045	-	-
Δ (GDP)	-	-	-	-	-5.346246	0.0000	-	-
Δ (GDP ²)	-	-	-0.111648***	0.0000	-	-	-	-
Δ (GDP ² *COVID-19)	-	-	-	-	0.001779	0.2581	-	-
Δ (GDP ² (-1))	-	-	0.551007**	0.0393	-	-	-	-
Δ (GDP ² (-2))	-	-	0.434927	0.1019	-	-	-	-
Δ (GDP ³)	-	-	0.010355***	0.0000	0.019902	0.0000	-	-
Δ (GDP ³ *COVID-19)	-	-	-	-	-	-	1.30E-06	0.9888
Δ (GDP ³ (-1))	-	-	-0.035880**	0.0412	-	-	-	-
Δ (GDP ³ (-2))	-	-	-0.029616*	0.0914	-	-	-	-
Δ (OILP*COVID-19)	-	-	0.105698***	0.0000	0.087731	0.0254	0.068528	0.0096
ECT (-1)	-0.474817***	0.0000	-0.780235***	0.0000	-0.787490***	0.0000	-0.544065	0.0000
Diagnostic test	F-statistic	Prob.	F-statistic	Prob.	F-statistic	Prob.	F-statistic	Prob.
RESET test	0.093785	0.7610	0.534663	0.4700	2.947099	0.0949	0.188514	0.6664
Normality test	2.053441	0.358180	4.956710	0.083881	1.169801	0.557161	2.085061	0.352561
LM test:	0.406967	0.6684	3.832978	0.0325	0.219950	0.8037	0.226495	0.7983
Heteroskedasticity test	0.904871	0.5218	0.719759	0.7471	1.234996	0.2995	0.952029	0.4858

 Δ is the first difference operator

***, **, and * denote significance levels of 1%, 5%, and 10%, respectively.

Table 7 Nonlinear ARDL estimation and diagnostic checks (CE-dependent variable)

	Model11 ARDL	(1, 0, 0, 1, 0, 0)
Long-run estimates Variable	Coef.	Prob.
GDP	−3.161667**	0.0071
GDP ²	0.581280**	0.0118
GDP ³	−0.028866**	0.0115
COVID-19*OILP-	0.068543	0.4136
COVID-19*OILP+	−0.124029**	0.0407
OILRENT	−0.262293***	0.0040
Short-run estimates		
Δ (GDP ³)	0.014309***	0.0000
ECT (−1)	−0.448954***	0.0000
Diagnostic test	F-statistic	Prob.
RESET test	0.094660	0.7599
Normality test	1.729676	0.421120
LM test:	0.444717	0.6441
Heteroskedasticity test	1.086816	0.3889

Δ is the first difference operator, and (+, −) represents the positive and negative changes of the cumulative function

** and *denote significance levels of 5% and 10%, respectively.

negative and statistically significant; in addition, the sign of the coefficient of the quadratic shape of the composite real GDP is positive and statistically significant. The results show an inverted N-shaped EKC in Saudi Arabia in models considering an oil price shock in the presence of the COVID-19 pandemic in the long run. In addition, when the dependent variable is carbon dioxide emissions, only the cumulative function of a positive change in the oil price in the presence of the COVID-19 pandemic has a negative impact on CE in long-run but is absent in the short term. This result seems the same confirmed by Sharif et al. (2020) in the USA. Furthermore, this result implies that the long-run impact of the positive shock on oil prices is not similar to the negative shock, which suggests the existence of asymmetric impacts in the long term (Toumi and Toumi 2019). The positive fluctuation in the cumulative function of oil price decreases carbon dioxide emissions by 0.124% (at 1% change) in the presence of the COVID-19 pandemic.

This estimation model includes diagnostic tests, such as the Breusch-Godfrey serial correlation LM test, normality tests, and the heteroskedasticity test of Breusch-Pagan-Godfrey, and stability tests, such as the Ramsey RESET test and CUSUM test and the CUSUM of squares test (Brown et al. 1975). These tests indicate that there are no problems of serial correlation and heteroskedasticity in terms of the residuals. Then, the results are normally distributed and hence the model is stable.

Conclusions and policy implications

To support the development of policy in terms of achieving the COVID-19 targets, this survey examined the important factors for achieving sustainable development goals while addressing the COVID-19 pandemic and increasing economic growth. This research investigates the impact of the COVID-19 pandemic on the KSA economy.

To achieve this goal, an autoregressive distributed lag (ARDL) model and a non-autoregressive distributed lag (NARDL) model are applied to capture both the long-run and short-run relationships between environmental quality and economic growth. In particular, we examine the effect of the COVID-19 pandemic under the setting of the N-shaped environmental Kuznets curve (N-shaped EKC). While considering the COVID-19 shock, the effects of oil price, oil rent, and economic growth on carbon dioxide emissions in the KSA are examined. The results of both the ARDL and NARDL bound testing approaches indicate that the inverted N-shaped EKC hypothesis is validated for the long term due to the COVID-19 pandemic.

The findings of our ARDL models resort the interaction term between the oil price and level and quadratic and cubic economic growth has a positive and statistically significant effect on enhancing the relationship between economic growth and environmental quality. Moreover, all coefficients of the level, quadratic, and cubic GDP are elastic and statistically significant. In addition, for the KSA, the interaction term between the oil rent level and quadratic and cubic economic growth has a negative and statistically significant effect on the relationship between economic growth and environmental degradation. Besides, all coefficients of the level, quadratic, and cubic GDP are inelastic and statistically significant.

Moreover, the results of our ARDL models resort a negative and significant relationship between oil rent (OILRENT) and carbon dioxide emissions in the long run and that an increase of 1% in the oil rent (OILRENT) will lead to the mitigation of environmental degradation by 0.25%. Moreover, in the presence of the COVID-19 pandemic, the oil price (OILP) is positive and statistically significant in the long run, and an increase of 1% in the oil price (OILP) will lead to an increase in CE by 0.23% at the 1% level of significance. Additionally, the long-term incidences of positive shocks on oil price in the presence of COVID-19 outbreak are not similar to the negative shock to CO₂ emissions, implying the existence of asymmetric impacts on carbon dioxide emissions in long-term forms.

About our second model (NARDL), we consider that the cumulative function of a positive change in the oil price in the presence of the COVID-19 pandemic has a negative impact on CE in long-run but is unobservable in the short term. Consequently, this result implies that the long-run impact of the positive shock on oil prices is not similar to the negative shock, which suggests the existence of asymmetric impacts in the long term.

The evidence presented here regarding the causal relationships between carbon dioxide emissions in one side and economic growth, oil rent, oil price, and COVID-19 outbreak in the other side has policy implications for the KSA. The efforts of the government that promote sustainable development goals in the Kingdom of Saudi Arabia for Vision 2030 could improve economic productivity by taking into consideration the impact of the COVID-19 pandemic and climate change. The KSA is trying a new economic and political approach by keeping the price of oil at the lowest level possible. In addition to the challenges that the COVID-19 pandemic has placed on the world, it has generated a significant disruption in oil prices. The KSA can improve its ability to achieve its sustainable development goals and shed light on urgent global issues by relying on non-oil sectors, adopting new policies regarding the development of efficient projects and employing green finance tools to achieve sustainable economic growth and reduce environmental pollution. For sustainable development goals, policymakers can boost investment especially in renewable energy and attempted to outperform significant actions where the green economy appears as a priority governmental dealing.

Our research implies that evidence of an oil price shock can be used to develop guidance for the macro-economy of the KSA. Our findings can help policymakers and investors engaged in settlement planning and evaluating potential avenues for economic profitability even under the COVID-19 shock.

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Author contribution Hassen TOUMI and Abdussalam ALJADANI designed the experiment and collect the dataset. The introduction and literature review sections are written by Mosbah HSINI, Said TOUMI, and Basma JALLALI. Hassen TOUMI and Abdussalam ALJADANI constructed the methodology section and empirical outcomes in the study. Hassen TOUMI and Mosbah HSINI contributed to the interpretation of the outcomes. All the authors read and approved the final manuscript.

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